Combination of discharge- and laser-produced plasmas for high brightness EUV light sources

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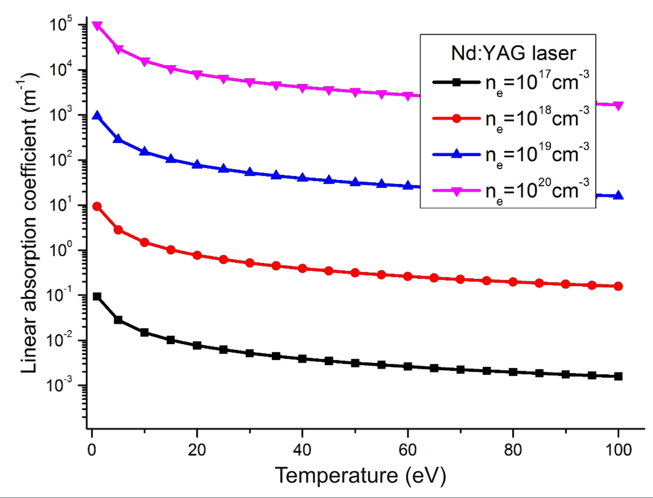
Introduction

For compact extreme ultraviolet (EUV, 5 nm - 30 nm) light sources a hybrid approach combining the techniques of discharge and laser produced plasmas can lead to the generation of highly brilliant incoherent EUV radiation.[1] To achieve this, the discharge of a hollow cathode triggered source produces a pinch plasma (typical values: $n_e = 5\cdot10^{18}\,\mathrm{cm}^{-3}$, $T_e = 10\,\mathrm{eV}$), which is used as a target for a pulsed Nd:YAG laser beam. The optical heating by the laser partially restores energy to the plasma, which is lost due to the EUV and other emissions. Thus, the time for the emission of EUV radiation can be prolonged and its etendue is reduced. Thereby, the so called laser-heated discharge plasma (LHDP) approach is a promising candidate for generating EUV radiation with minimum required laser pulse energy and discharge currents.

Theory of Laser Heated Discharge Plasma

The plasma is created in a hollow cathode triggered discharge. The dense pinch plasma serves as a target for laser beam. The laser is focused into the pinch and is mainly absorbed via **inverse Bremsstrahlung**. Radiation losses of the plasma are compensated by the coupled laser energy. This leads to an **increased EUV output** and **smaller emitting volume**, thus to a higher radiance[2].



$$\alpha_{ei} = \frac{n_e^2 e^6}{6\sqrt{3}\, n\, \varepsilon_0^3 c\, \hbar \omega_L^3 m_e^2} \sqrt{\frac{m_e}{2\pi k_B T_e}} \left(1 - \exp\frac{-\hbar\omega_L}{k_B T_e}\right) \bar{g}$$

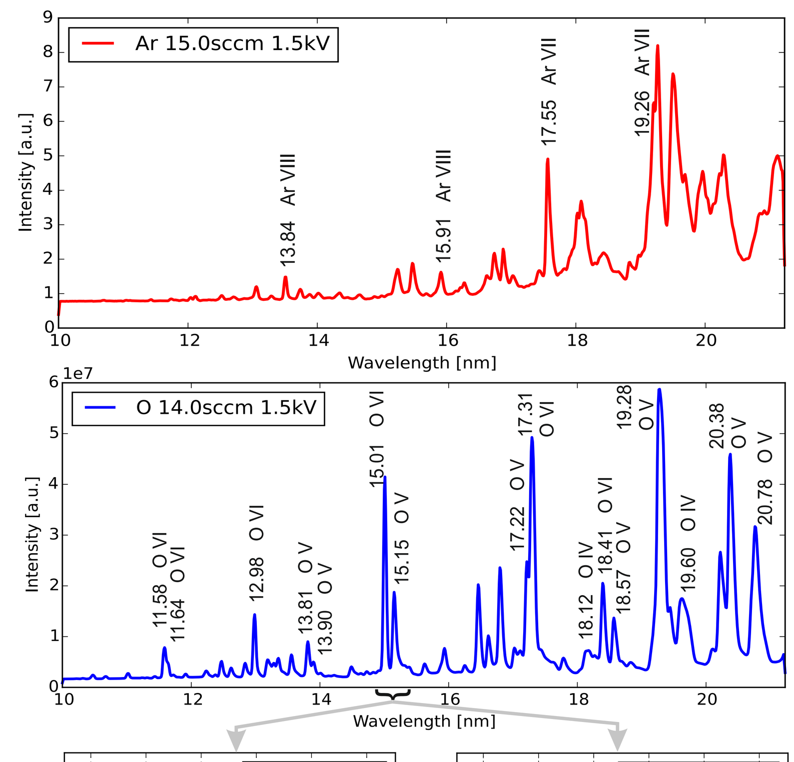
Absorption coefficient for electron-ion inverse bremsstrahlung.
ω_L, laser frequency,
n, real part of the refractive index
$\bar{g}$, averaged Gaunt-factor.

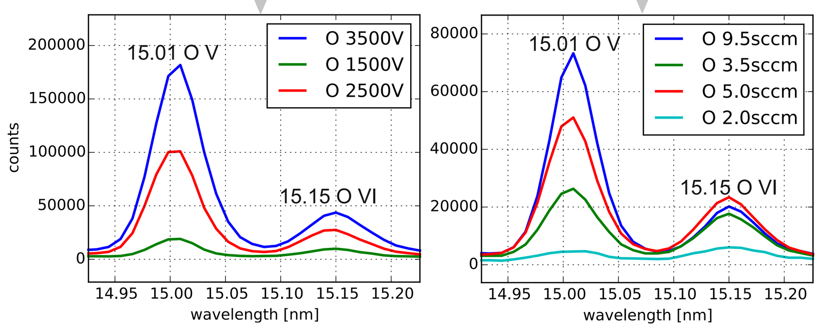
Simulated linear absorption coefficient for electron-ion inverse bremsstrahlung at different plasma parameters

Parameters of the plasma source

Plasma source	
Capacity	1.1 µF
Inductivity	10 nH
Resistivity	22 mΩ
Voltage	≤ 3.5 kV
Energy per pulse	≤ 6.7 J
Repetition rate	≤ 30 Hz
Gases	Ar, Xe, N_2, O_2
Workin pressure	~ 10^{-2} mbar
Trigger	Hollow cathode with active electron emission, ***delay:*** 350 - 500 ns

Laser	
Type	Nd:YAG
Wavelength	1064 nm
Energy per pulse	≤ 820 mJ
Pulse duration	~ 11 ns
Repetition rate	≤ 10 Hz
Trigger type	Pockel cell Q-switch, ***delay:*** 100 ns





Argon (top) and Oxygen spectrum (middle) with line identification [4], different capacitor voltages at 9.5 sccm (left) and different flows at 2 kV (right). Higher capacitor voltage leads to higher intensity and no change in spectrum. Higher pressure (gas flux) leads to a pronunciation of higher ionization levels.

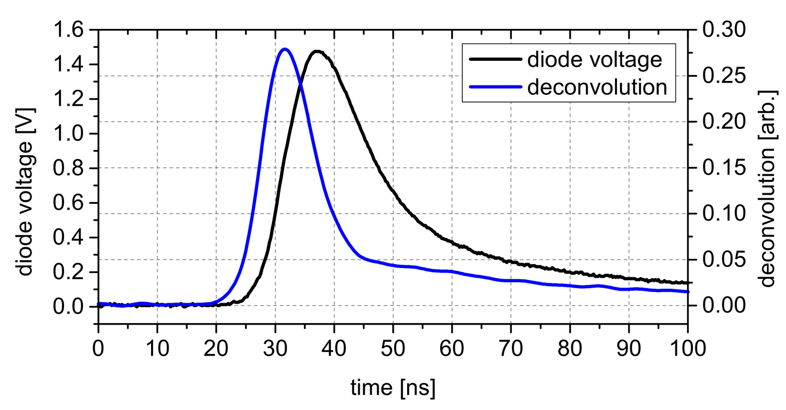
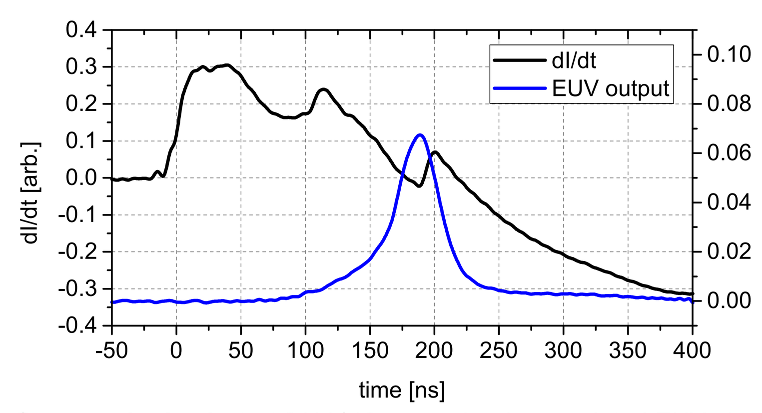


Photo diode signal of a single ***laser pulse at 400 mJ****. The deconvolution eliminates the characteristic diode response and shows the real pulse shape with a* ***FWHM of 11 ns****.*



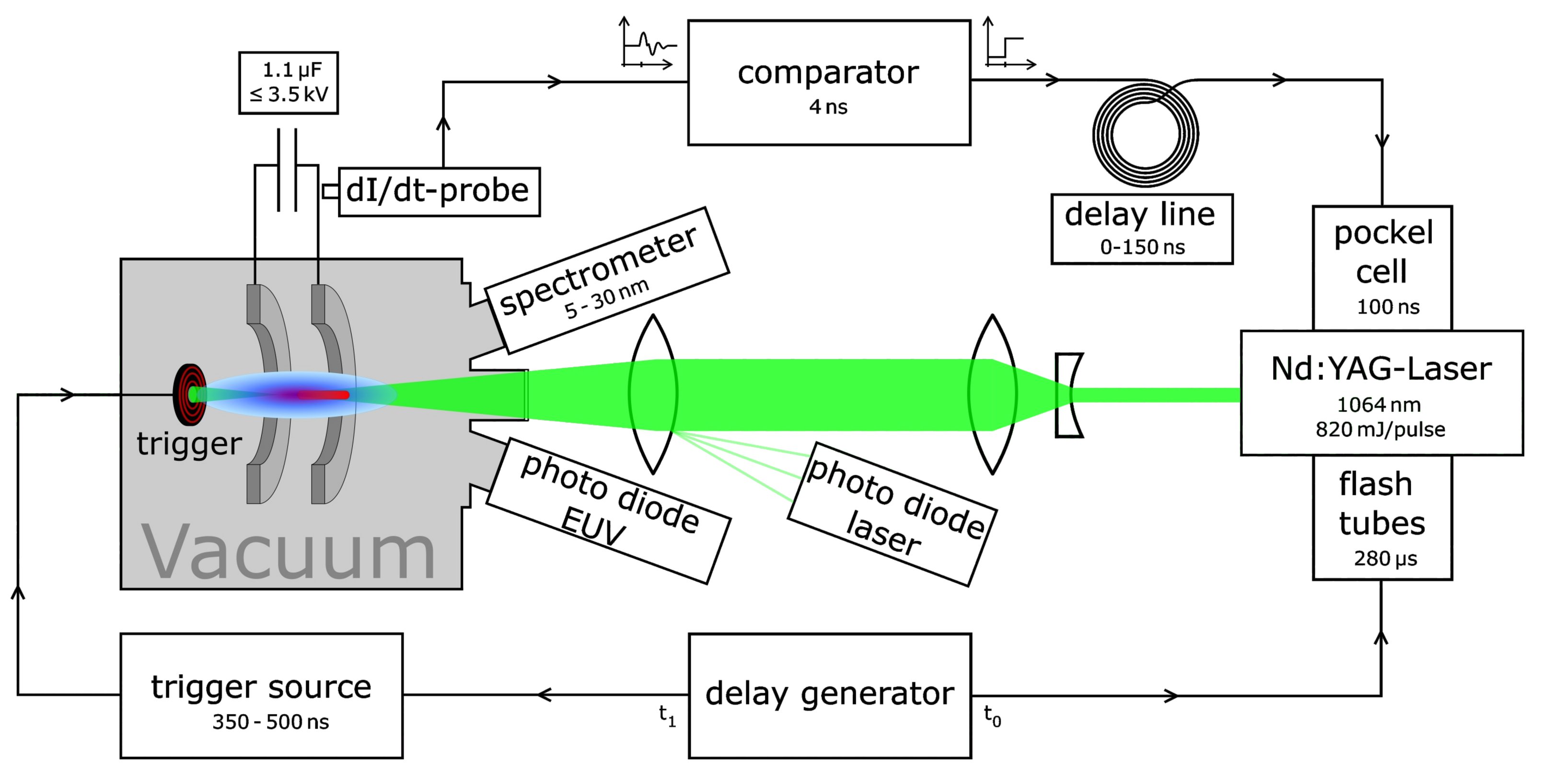
Oxygen single shot *at 2 kV / 10 sccm, the deconvoluted EUV photo diode signal shows the real point of* ***EUV emission*** *after a 200 nm Al filter.*

Experimental setup of LHDP measurements

After the laser flash tubes and the plasma source are triggered, the first rise in current is detected by a dI/dt probe. This signal is converted by a custom high speed comparator and used to set off the Q-switch within the laser.

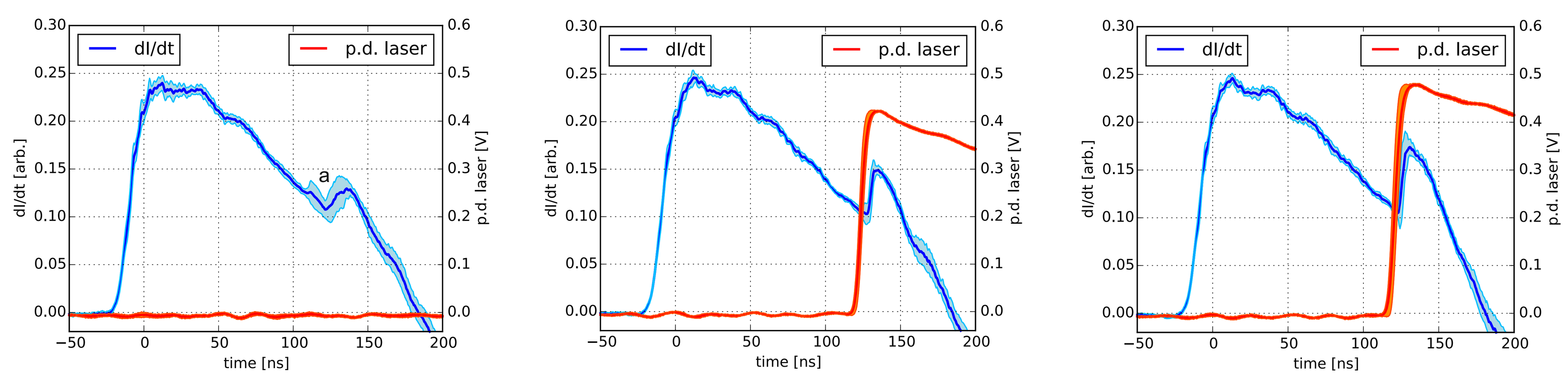
The laser photo diode detects the laser pulse from a stray reflextion. In combination with a second dI/dt probe the exact timing of the experiment can be monitored.

Beam-blocking molybdenum plate on trigger electrode with visible imprint of the laser profile



Simplified layout of the LHDP experiment. The laser beam is widened to 20 mm and focussed with 400 mm focal length through a glass window on the center port. Temporal adjustment is done by a cable delay line. A minimum delay of 120 ns is achieved and only limited by the inherent temporal properties and distances of the components.

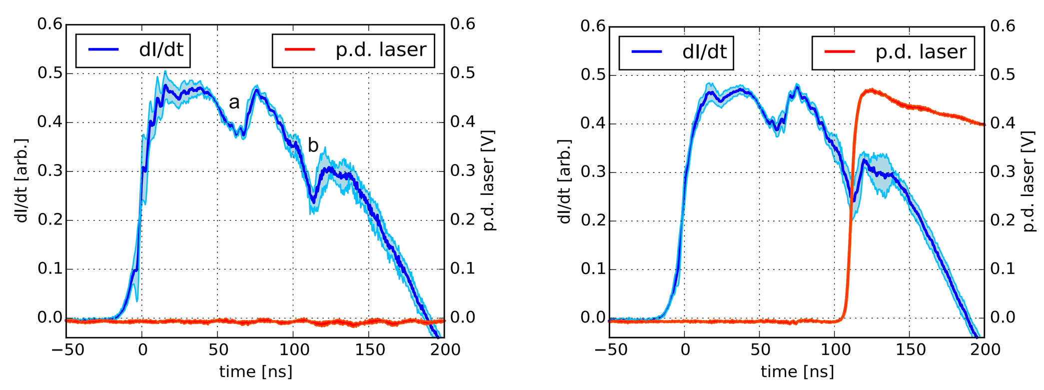
Results



dI/dt and laser photo diode signal of 15 sccm ***Argon at 1.5 kV*** */ 1.1 J. At this energy and pressure no EUV light is emitted during the first pinch. Coupling the laser pulse into the plasma during this phase, leads to a significant rise in conductivity. The effect scales with laser energy:* ***450 mJ*** *(middle) and* ***680 mJ*** *(right).*

During the **first pinch** (a), the plasma temperature and thus the thermal pressure is low enough, to fit the absorption requirements.

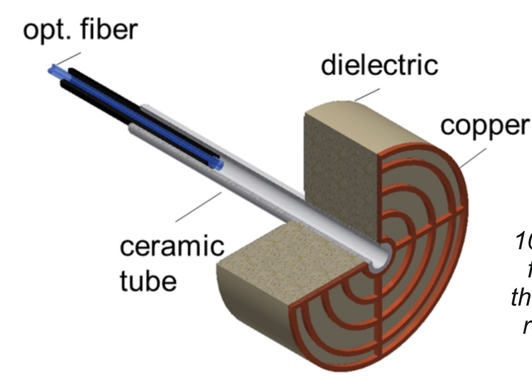
The **second pinch** (b) is hotter and as a result less dense. This puts the plasma into a regime where no interaction between laser and plasma appears.



dI/dt and laser photo diode signal of 9 sccm ***Argon at 2.7 kV*** */ 4 J. At this energy and pressure strong EUV light is emitted during the second pinch. There is no significant influence of the 1064 nm laser pulse at* ***680 mJ*** *visible.*

Outlook

- Analyze radiation in first pinch via **UV / Vis** spectrometer and photo diode
- New trigger electrode which allows to analyze the **residual laser** intensity
- Utilizing **longer wavelength** laser (3 µm) is promising for hot and less dense plasma
- Analyze spectral and spatial evolution of plasma via **micro channel plate**
- High resolution pinch images with a **custom zone plate**



New trigger electrode with 1064 nm monomode fibre connected to the center to analyze residual laser light.

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